ANSI/AIAA
R-020A-1999

American National Standard

Recommended Practice for Mass Properties Control for Satellites, Missiles and Launch Vehicles

Sponsored by

American Institute of Aeronautics and Astronautics

In cooperation with

Society of Allied Weight Engineers

Approved August 23, 2000

American National Standards Institute

Abstract

This Recommended Practice provides a methodology for the management of the growth of mass properties during the development of aerospace flight vehicles. It is particularly applicable to missiles, satellites, and launch vehicles. The standardized methodology is consistent with former Mil-Std 1811 and is based on planning, controlling, and reporting at each stage of product or system development.

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Recommended practice: mass properties for satellites, missiles, and launch vehicles/generated by AIAA Design Engineering Committee on Standards in cooperation with the Society of Allied Weight Engineers, Government/Industry Missiles and Space Systems Committee.

p. cm.

"ANSI/AIAA R-020A-1999"

Includes bibliographical references.

ISBN 1-56347-387-9 (softcover), 1-56347-454-9 (electronic)

1. Space vehicles—Design and construction—Standards. 2. Space Vehicles—Weight—Standards 3. Space vehicles—Propulsion systems—Standards. I. Society of Allied Weight Engineers. Government Industry Missiles and Space Systems Committee. II. AIAA Design Engineering Committee on Standards.

TS875.R43 2000
629.46'02'1873—dc21

99-089674

Published by
American Institute of Aeronautics and Astronautics
1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344

Printed in the United States of America

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Foreword

This Recommended Practice for Mass Properties Control of Satellites, Missiles and Launch Vehicles is sponsored by the American Institute of Aeronautics and Astronautics (AIAA) as part of its Standards Program.

This recommended practice is produced by the AIAA Design Engineering Committee on Standards in concert with the Society of Allied Weights Engineers, Inc (SAWE). The purpose is to provide a comprehensive methodology for mass properties control through the multiple phases of hardware development. It serves to link existing mass properties documentation between the AIAA, SAWE and United States Government, and to amplify those areas of mass properties control which may need clarification for good engineering practice. This document supersedes the former AIAA document, "Estimating and Budgeting Weight and Power Contingencies for Spacecraft Systems" (ANSI/AIAA G-020-1992).

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The following are part of the editorial committee: Glen S. Mathews, Roger L. Belt, and Alvin W. Sheffler.

Certain Recommended Practices published by the Society of Allied Weight Engineers are referenced in this standard. The SAWE documents may be obtained from the Society. The postal address is:

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The AIAA Standards Executive Council accepted the document for publication in August 2000.

1 Scope

The management and control of mass properties is of fundamental importance in the design and manufacturing process of aerospace hardware. Mass properties are to be managed and controlled as any other system performance parameter. They need to be allocated, analyzed, controlled and verified. The full set of mass properties, including mass, center of gravity, moments of inertia and products of inertia need to be tracked throughout the program to assure compliance with the program requirements.

2 References

The following documentation is referenced in this Recommended Practice. If a conflict exists between this Recommended Practice and these referenced documents, the user may contact AIAA for aid in resolving the conflict.

Mil-Hdbk-1811, "Mass Properties Control for Space Vehicles", August 1998

SAWE Recommended Practice #9, "Weight and Balance Control System for Guided Missiles and Space Launch Vehicles"

SAWE Recommended Practice #10, "Weight and Balance Data Reporting Forms for Guided Missiles and Space Launch Vehicles"

SAWE Recommended Practice #11, "Mass Properties Control of Space Vehicles"

SAWE Recommended Practice #6, "Standard Coordinate System for Reporting the Mass Properties of Flight Vehicles"

3 Definitions

3.1 Mass Properties

The mass properties of a given item include the mass, center of gravity (CG), mass moments of inertia and the mass products of inertia of that item. Although the term "weight" is commonly used in practice, the proper term is "mass" and that term is used throughout this document.

3.2 Mass Properties Categories

Mass properties are typically categorized as "estimated", "calculated", or "measured" (or "actual") according to the method used to determine their value. The percent of the hardware mass that is based on each of these categories is an indication of the confidence that can be placed in the reported mass properties data. In general, the following definitions apply:

3.2.1 Estimated Properties

Mass properties determined from preliminary data, such as sketches or calculations from layout drawings, are typically considered to be in the estimated category.

3.2.2 Calculated Properties

Mass properties determined from released drawings or controlled computer models are typically considered to be in the calculated category.

3.2.3 Measured Properties

Mass properties determined by measurement or by comparison of nearly identical components for which measured mass properties are available are in the measured category.

Figure 1 is an illustration of related terms commonly used in reporting mass properties during the development of aerospace hardware. The definitions of these terms are given here in logical sequence rather than alphabetical order.

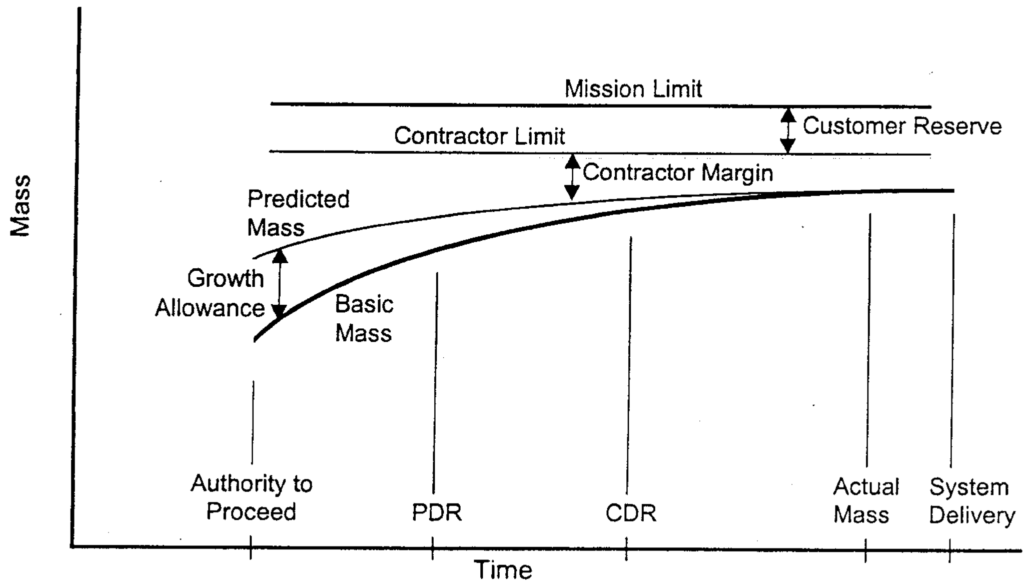

Figure 1 — Mass Control Parameters (Idealized to illustrate definitions)

3.3 Mass Control Parameters

The Basic Mass Properties of an item are the mass properties data based on an assessment of the most recent baseline design. This design assessment includes the estimated, calculated, or measured mass properties, and includes an estimate for undefined design details. The mass growth allowance is not included.

3.3.1 Mass Growth Allowance

The Mass Growth Allowance is the predicted change to the Basic Mass Properties of an item based on an assessment of the design and the fabrication status of the item, along with an estimate of the design changes that may occur. The design changes may be implemented in order to satisfy the contracted design requirements during the development process. The Mass Growth Allowance associated with these design changes compensates for the lack of design maturity. Configuration changes driven by major contract or requirements changes are not included in the mass growth allowance.

3.3.2 Predicted Mass

The Predicted Mass of an item is the Basic Mass plus the Mass Growth Allowance, and is intended to estimate the final mass at the end of the development cycle.

3.3.3 Contractor Limit

The Contractor Limit Mass of an item is established early in the program based on prior experience with similar hardware items. It includes a margin above the Predicted Mass to allow for uncertainties during the design cycle. The Contractor Limit is intended to remain constant through the course of the program.

3.3.4 Contractor Margin

The Contractor Margin is the difference between the Contractor Limit and the Predicted Mass.

3.3.5 Customer Reserve

The Customer Reserve may be defined by the customer acquiring the hardware from the contractor. This value is defined by the customer according to the agreements of the contract.

3.3.6 Mission Limit

The Mission Limit is the maximum mass that can still satisfy all of the mission performance requirements.

4 Design and Development Process

The program phases related to mission or project development generally follow the common set of milestones shown here. Mass Properties Reviews are to be conducted at each milestone and Mass Properties Reports generated:

Bid	Proposal or Bid Stage
CoDR	Conceptual Design Review
PDR	Preliminary Design Review
CDR	Critical Design Review
PRR	Pre-shipment Readiness Review
FRR	Flight Readiness Review

The following sections define these stages and provide recommended action to assure the Mass Properties Control Process is effective at each stage. The findings at each stage are to be documented in the Mass Properties Reports, as defined in Section 5.2.

Additional information on the mass properties control process during the design and development phase can be found in Mil-Hdbk-1811 as well as SAWE Recommended Practice #9, #10 and #11. In all phases, consistent coordinate systems should be defined for the mechanical layout of the aerospace hardware. SAWE Recommended Practice #6 may be used to establish these coordinate systems and all reports should reference these coordinates in a consistent manner.

4.1 Bid

The initial design concept is generated in the bid or proposal stage. This effort may be a concept proposal, RFP response, or baseline design for future development. Mass properties are generally based on similar designs from the contractors experience base.

4.2 CoDR

The objective of the Conceptual Design Review is to define and assess the proposed design approach and to verify that it has a high probability of satisfying the mission requirements. The following subjects should be reviewed at this stage to determine the uncertainties and possible growth or other changes on the mass properties.

Statement of Work / Design Requirements
Initial design
Trade studies
Alternate configurations
Selection of critical parts
Preliminary analyses
Definition of environments
Interface requirements
Mass budget
Power budget
Development test plans
Mission requirements
Operations and Maintenance requirements
Human factors
Customer Furnished Equipment

Project planning
Software approach

The CoDR will normally be scheduled at a time when the design concept is sufficiently developed to permit a valid assessment and prior to the start of development testing.

4.3 PDR

The objectives of the Preliminary Design Review are to examine and validate the design approach as related to the project or mission requirements. The following items may affect the mass properties of the final deliverable and are to be reviewed at the PDR level to assess the possible impact to the mass properties:

Mechanical design layouts
Circuit designs
Design analyses
Performance analyses
Results of development testing
Customer furnished equipment requirements
Mass budget
Identification of long lead items
Manufacturing and qualification test planning
Status of reliability, quality assurance, and systems safety programs
Status of planning for data retrieval, analysis, and publication
Function / system block diagram
Power schematic
Power budget

The PDR will normally be scheduled at the completion of the preliminary design stage and prior to the detail design of flight hardware.

4.4 CDR

The objectives of the Critical Design Review are to examine details of the final design and mission, fabrication plans, and flight acceptance test planning as related to project / mission requirements. The following items may affect the mass properties of the final deliverable and are to be reviewed at the CDR level to assess the possible impact to the mass properties:

Design requirements statement
Updated final design and analyses
90% engineering drawing release
Development test results
Calibration test results
Functional and performance test results
Mass budget
Reliability, quality assurance, and safety programs
Review of the plans for data retrieval, analysis, and publication
Instrument requirements statement
Power budget
Qualification test plans

The CDR will normally be scheduled at the completion of the detailed design stage and prior to the fabrication of flight hardware. If necessary, "proto-qual" hardware or "qual hardware" may have been included.

4.5 PRR

The objectives of the Preshipment Readiness Review are to verify that the flight hardware conforms to all applicable requirements and is ready for shipment and subsequent integration into the next assembly.

The PRR will normally concentrate heavily on the results of acceptance testing. The mass properties control process is in the final review stage with focus on the following topics for verification:

Mass budget
Power budget
Validating the quality of the hardware
Confirming that the hardware is flightworthy and will perform properly under the simulated flight environment
Actual mass properties report
Actual power report
Assessing that the mission objectives will be met
Compliance with mission requirements and specifications
Refurbishment and recalibration plans (when required)
Shipping and storage plans
Confirmation of compatibility with all interface, weather protection, and contamination control plans
Resolution of all failures or anomalies during test
Status of safety and reliability analyses and verification of compliance with documentation requirements
Qualification and acceptance test reviews

The Pre-shipment Readiness Review will normally be held after the completion of major acceptance testing, including mass properties system level testing, but prior to shipment of flight hardware.

4.6 FRR

The objectives of the Flight Readiness Review are to perform a final assessment of the ability of the equipment to satisfy all of the mission requirements and to verify that the equipment is fully ready for flight operations. The mass properties reports are finalized with reviews of the following topics:

Total mass properties report
Total power report
Flight readiness of all hardware, software, and operational elements
Completed ground support operations
Interfaces with other flight equipment
Ground based mission support requirements
Flight operations plans
Data retrieval and processing, including ground network compatibility tests
Public information plans

The Flight Readiness Review will normally be held as near as practicable to the flight date.

5 Mass Properties Control Process

5.1 Overview of Control Process

The Mass Properties Control Process is an integral part of the design, development, manufacture, assembly, test, launch, and orbit insertion of the hardware. With this breadth of scope, the Mass Properties Control Process must be a fundamental part of program planning to assure full mission success within cost and schedule constraints. The following sections provide the recommended plans, analysis, verification, and reports required to meet this objective.

Further information may be found in Mil-Hdbk-1811 and SAWE Recommended Practice #9, #10 and #11 for missiles, launch vehicles and space vehicles.

5.2 Documentation

Basic documentation consists of two types: Plans and Reports.

Plans define the program management processes and methods for controlling and measuring hardware mass properties.

Reports provide visibility into the hardware configuration and design maturation through the development process.

The Plans and Reports described herein are recommended baselines for practice.

5.2.1 Control Plan

The Mass Properties Control Plan defines the management program and the procedures to be used for mass properties analysis and control during all phases of the program. The objective of the Plan is to provide an organized process that can be effectively implemented early in the development phase and carried through to hardware operation. Addressing the total program span assures the hardware mass properties are properly defined, controlled, and verified. An overview of the verification process should be addressed in the Control Plan, while the details should be addressed in a separate Verification Plan, per Paragraph 5.2.2.

A recommended Mass Properties Control Plan should contain the following information:

Introduction
Scope of Control Plan within the Program
Implementation and management of Control Process
Mass Properties Control
Mass Properties Control Board Definition and Authority
Mass Properties Control Process
Mass Definitions
Design and Trend Assessment
Mass Properties Personnel Responsibilities
Mass Growth Allocation & Depletion Schedule
Mass Growth Allocation & Depletion Schedule Operation
Mass Change Codes
Subsystem Functional Coding

Mass Properties Verification
Verification Plan Definition
Design Phase Verification and Control Process
Production Phase Verification Process
Pre Launch Measurements
Subcontractor Input
Specified Mass and Mass Growth Allocations
Subcontractor Verification Plan
Subcontractor Mass Properties Control Plan

5.2.2 Verification Plan

The Verification Plan defines the methods to be used to verify the mass properties data. The Plan addresses the process for determining piece part, sub-assembly, and assembly level verification.

The Verification Plan should be formulated in the early stages of a program. For example, mass properties measurement requirements could affect the hardware design and must be addressed early in the design phase. In other cases, procurement of long lead measurement equipment may be required or other organizations on the program may be affected.

Typical Case Study: The cg must be known very accurately relative to a set of thruster nozzles. However, these nozzles may be too fragile, inaccessible, or too inaccurately aligned to be physically referenced, and no other reference to the nozzles is available on the vehicle. Therefore, an accurate secondary reference must be established. This could require precisely machined rings, hard points, or optical references to be designed into the vehicle and to be traceable to the vehicle coordinate system as well as to the nozzles. In this example, the apparently simple requirement to maintain cg control relative to the thrusters produces a significant hardware layout requirement.

Another example that is easily overlooked is the need for specialized handling features (such as inserts and fixtures) used during various stages of assembly. The mass of these fixtures may significantly affect the structural loading.

In all cases, components should be measured as soon as available from manufacturing to show adverse trends of mass growth as early in a program as possible. Discovering an over limit condition at final assembly, usually late in a program, will result in little time or budget to rectify the problem.

Reference SAWE Recommended Practice #11 for a detail description of the Verification Plan content. As a minimum, the Verification Plan should include the following information:

List of components, subassemblies, and assemblies to be verified
Requirements to be verified
Hardware limitations (such as hinges with a moment limit)
Accuracy required to meet program requirements
Uncertainty analysis to determine accuracy
Method of measurement and justification for method selected
Equipment to be used
Reference coordinate system and datum
Recommended method or process to assure proper verification

5.2.3 Status Reports

Periodic Status Reports provide insight to the status of the mass properties of the program throughout all its phases. The basis (Estimated, Calculated, or Measured) of each component mass shall be included as part of the recorded component data. Totals of each of these categories shall be recorded to provide an indication of the mass properties confidence. Reference SAWE Recommended Practice #11 for a detail description of report content. As a minimum, status reports should include the following information:

Summary of Mass Properties Values and Level of Confidence
Sequential Mass Properties during Operational Lifetime
Mass Properties Monitoring of Margin Status
Changes since last Report
Potential Changes
Customer Furnished Equipment
Reference Coordinate System
Mass History

5.2.4 Detail Reports

Periodic Detailed Reports provide further insight into the status of the mass properties of the program than the normal status report. These reports provide information on the trends that may have a major impact on the program. Reference SAWE Recommended Practice #11 for a detail description of report content. As a minimum, detailed status reports should include the following:

All elements in Section 5.2.3
Detail Mass Statement
Design Data that have major impacts on subsystem masses.

5.2.5 Trend Analysis Report

For a variety of reasons, programs generally experience mass growth over time. It is recommended that a projected mass trend be generated early in the program, then monitored and updated on a regular basis as the program proceeds. An idealized version of the mass trend is shown in Figure 1. An illustration of the difficulty in controlling the mass and predicting the trend is illustrated by the more realistic example in Figure 2.

The example illustrated in Figure 2 shows the effects of large uncertainty and lack of mass control in the early stages of a program. By Month 5 in this example, mass reduction techniques are implemented and the mass begins to decline. At this early stage, however, the design is not adequately defined to allow the reduction of the Mass Growth Allocation. By Month 15, the design maturity is advanced enough to reduce the contingency and to begin the evolution of the Mass Growth Allowance toward lower values. By Month 24, many Measured Masses are available and the Basic and Predicted Masses converge.

The mass growth allowance applied to the mass is directly related to the maturity of the design. The following approach is recommended to categorize the maturity of each component, assembly, and system in a given program and to assign a mass growth allowance to the estimated mass. The values presented in Table 1 are typical for a variety of programs and may be employed directly with reasonable confidence. Contractor experience with similar designs may justify a different set of mass growth allowance values.

The Codes defined in Table 1 for the stages of Design Maturity are suggested for use in the Mass Properties Reports in Section 5.2 to assure consistency between programs.

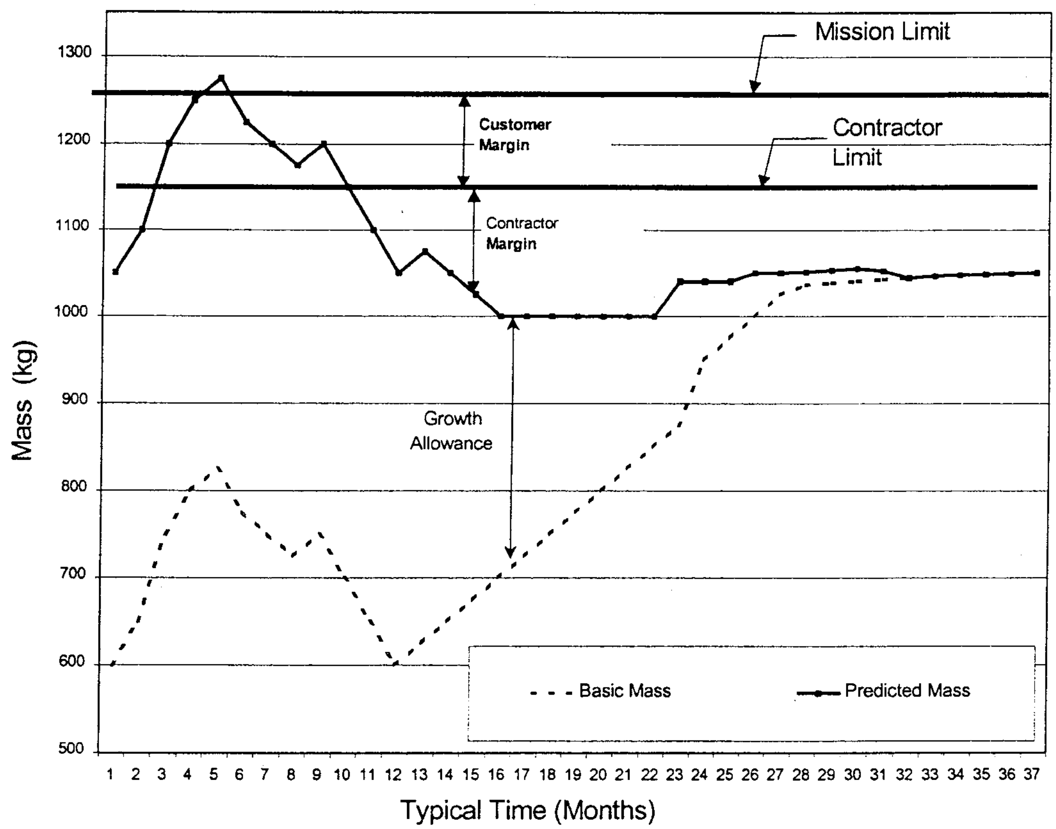

Figure 2 — Program Mass Tracking

5.3 Analysis

Mass Property Analysis follows the methodology defined in the Mass Properties Control Plan and provides direct input to the various reports. The recommended level of analysis to be conducted on the flight hardware and selected ground support equipment is defined in the following sections.

5.3.1 Flight Hardware

The Mass Property Analysis should be conducted on each configuration of the Flight Hardware and include any unique configurations that may occur during the launch, flight, orbit insertion sequence, and during the mission lifetime. Typical changes in configuration include deployable items and fuel depletion.

5.3.2 Ground Support Equipment

Analysis of the combined Ground Support Equipment (GSE) and Flight Hardware may be required during integration and test operations. For example, the flight hardware may be in partial stages of assembly with non-flight equipment that may affect the balance and loading on the support points. This could have a significant effect on the structural integrity of the flight hardware.

Table 1 – Recommended Mass Growth Allowance as a Percentage of Estimated Mass

Code	Design Maturity (Basis for Mass Determination)	Percent Mass Growth Allowance									
		Electrical/Electronic Components			Structure	Thermal Control	Propulsion	Batteries	Wire Harnesses	Mechanisms	Instrumentation
		0-5 kg	5-15 kg	>15 kg							
E	**Estimated** (preliminary sketches)	30	20	15	18	18	18	20	50	18	50
L	**Layout** (or major modification of existing hardware)	25	20	15	12	12	12	15	30	12	30
P	**Pre-Release Drawings** (or minor modification of existing hardware)	20	15	10	8	8	8	10	25	8	25
C	**Released Drawings** (calculated value)	10	5	5	4	4	4	5	5	4	5
X	**Existing Hardware** (actual mass from another program)	3	3	3	2	2	2	3	3	2	3
A	**Actual Mass** (measured flight hardware)	0	0	0	0	0	0	0	0	0	0
CFE	**Customer Furnished Equipment**	0	0	0	0	0	0	0	0	0	0

5.3.3 Configuration Definitions and Limitations

Although flight events are clearly defined and analyzed to assure proper performance, each stage of the integration and test process also require a definition of the flight hardware assembly and GSE configuration. Knowledge of specific limitations such as lift point strengths, CG range, etc. are required to assure safety during all assembly and transport operations. The analysis of these non-flight events should also be included in the Mass Properties Analysis.

5.4 Verification

Mass Properties Verification is the confirmation, or assurance, that the required mass properties are known within established limits. The following sections provide recommended criteria for establishing which mass properties are considered "required", how "limits" can be established, and a plan of verifying these required properties.

5.4.1 Determination of Mass Properties Verification Requirements

First determine which mass properties require verification. Based on individual program requirements, specific flight events generally require specific knowledge of selected flight hardware mass properties and the allowable tolerances on these values. In some cases, the mass properties need to be defined early in the design process and controlled to be maintained within defined tolerances. In other cases, a wide tolerance of mass properties may be acceptable, but an exactknowledge of the as-built assembly is needed. These cases illustrate the need for a definition of the critical or "required" mass properties for selected assemblies.

5.4.2 Determination of Mass Properties Limits

The allowable limits of the mass properties parameters generally define two distinct criteria to be established in the Verification Program

- Establish an Acceptance Criteria for the hardware assembly in terms of maximum and minimum mass, CG location, and inertia that is consistent with the Verification Requirements.
- Establish the accuracy required in conducting the measurements in the verification process that is consistent with the Verification Requirements.

The Mass Properties Limits are to be defined in the Verification Plan and addressed in the specific procedures used to determine these parameters.

5.4.3 Mass Properties Verification Process

Verification can be done by direct or indirect measurement, by analysis or by a combination of both. Based on the accuracy required, the methods of verification shall be selected that are consistent with the required levels of accuracy at each phase of assembly. Verification shall be performed in accordance with Verification Plan.

5.4.3.1 Verification Requirements

Selected mass property parameters, and their conformance to the limits, should be verified by the contractor. Verification should be accomplished by approved analytical methods, by test, or by a combination of both. The verification methods should be selected early enough in the program to provide time for the acquisition, modification, or preparation of measurement equipment and sites. The verification plan should also include the planned general procedures for the measurement tests.

5.4.3.2 Verification Procedures

Mass properties measurement tests should be conducted in accordance with program approved, documented procedures.

5.4.3.3 Notification of Measurement

The contractor may require the customer to be present at the performance of critical measurements. In such cases, proper notification should be given prior to testing. Minimum prior notification should be considered one week. Exceptions such as the weighing of small hardware items may be made by mutual agreement of contractor and customer.

5.4.3.4 Test Conditions

The item should simulate the dry flight/operating condition; and be at least 95-percent complete by mass, excluding hazardous components or components not normally installed at the measurement site. A mass properties engineer should verify the configuration of the item and record mass properties related data for all missing items, added non-flight/operating items, and tare items.

5.4.3.5 Data Records

Mass properties verification data should be documented and made available for review on the current program as well as archived for reference on future programs.